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## The prediction of coating geometry from main processing parameters in laser cladding

Ondřej Nenadl<sup>a,\*</sup>, Václav Ocelík<sup>a</sup>, Armin Palavra<sup>a</sup> and Jeff Th. M. De Hosson<sup>a</sup>

<sup>a</sup>*Materials innovation institute (M2i), Department of Applied Physics, University of Groningen  
Nijenborgh 4, Groningen, 9474 AG, The Netherlands*

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### Abstract

Based on a recently published recursive model describing the geometry of laser clad coatings and on experimental track characteristics we propose specific functions to describe the geometry of laser clad coatings formed by overlap of individual tracks depending on the processing parameters. The recursive model provides a very good description of the whole geometry of the coating from the Height  $H$  and width  $w$  of a single laser track for any overlap ratio  $OR$ . We have shown in the past that the height and width of a single track are well correlated with the main laser cladding processing parameters for both coaxial and side cladding set-ups. Combining these two approaches leads to prediction of the complete geometry of laser clad coatings from basic processing parameters. These parameters are: Feeding rate  $F$ , Laser beam scanning speed  $S$  and overlap ratio  $OR$ . The character of the functions that describe the height and waviness of the final coating is the same for both coaxial and side cladding set-ups.

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**Keywords:** Laser Cladding; Coatings; Surface; Processing Parameters

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### 1. Introduction

Laser cladding is a technique that allows for the deposition of thick protective coatings on low-cost substrates. The process can be described as an addition of one material by cladding on the surface of a substrate, where the heat source is a high power laser beam. The resulting thickness of the clad is typically 50  $\mu\text{m}$  to 2 mm in a single step. Once a thicker protection layer is needed, the process can be applied again. In particular, laser cladding by powder

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\* Corresponding author. Tel.: +31-50-3634890 .  
E-mail address: [o.nenadl@rug.nl](mailto:o.nenadl@rug.nl)

injection leads to high quality, thick coatings with metallurgic bonds and minimal heat input into the work piece, Toyserkani et al. (2005).

The laser cladding operational window can be defined in terms of laser power  $P$  [W], laser beam scanning speed  $S$  [mm/s] and powder feeding rate  $F$  [mg/s]. These are the three key parameters as they can be easily controlled and have a strong effect on the final outcome of the clad layer. A complete description of the cladding process is complex as it also depends on additional parameters such as laser beam spot size, laser beam energy distribution, carrier and shielding gas used, how exactly the powder is fed, etc. Difficulty with the description of the process is due to many different interactions and various physical phenomena. Nevertheless, our work has shown particular statistical relationships between the main laser cladding process parameters and geometrical characteristics of laser track for coaxial, de Oliveira et al. (2005), and side laser cladding nozzles, Ocelík et al. (2007), respectively.

Furthermore, since the laser cladding process is based on heat transfer among the laser beam, the substrate and powder, and mass transfer between the powder flow and the molten surface it is useful to define *combined parameters*, Felde et al. (2003). The key quantities are: the amount of powder provided per unit length of the laser track  $F/S$  and the total heat input per unit length of the laser track  $P/S$ . It has been shown experimentally that over a wide range of processing parameters the clad height,  $H$ , depends linearly on the  $F/S$  parameter with the laser power having a minimal effect. Similarly the width,  $w$ , of the laser track linearly depends on  $P/\sqrt{S}$  and the clad area,  $A_c$ , is controlled by the  $\sqrt{P} \cdot F/S$  parameter. These empirical dependencies were observed for both, side and coaxial cladding setups with high values of the correlation coefficient ( $R > 0.9$ ) for cladding of Ni and Co based coatings on iron base substrates, de Oliveira et al. (2005) and Ocelík et al. (2007). Figure 1 shows an example of these empirical dependencies.

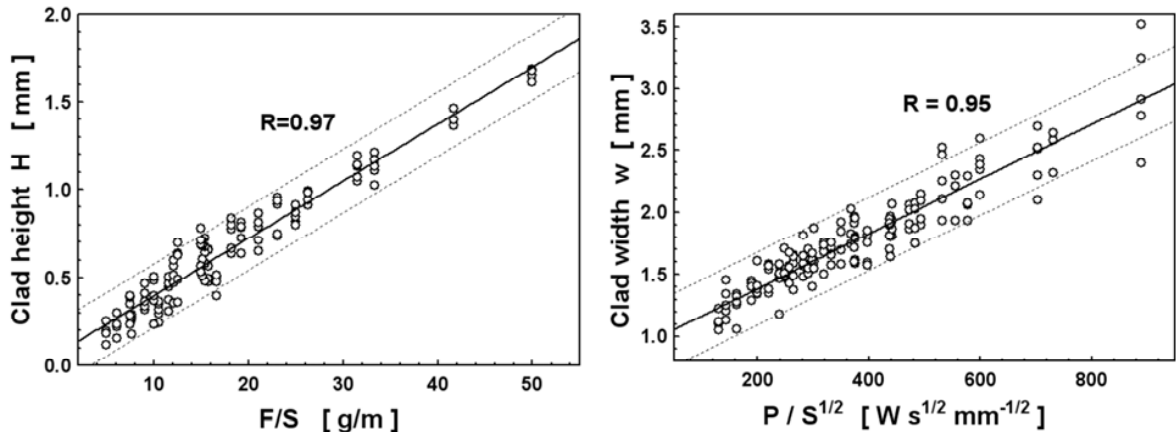


Fig. 1. Empirical dependence of laser track height,  $H$ , and laser track width,  $w$ , on combined processing parameters observed for coaxial and side cladding setups for Ni and Co based alloy cladding; from Ocelík et al. (2007) (left) and from de Oliveira et al. (2005) (right).

These dependencies were experimentally confirmed on successive experimental and modelling observations for a wide range of cladding and substrate materials, Kumar and Roy (2009), Davim et al. (2008), Ni et al. (2011) and Liu et al. (2013).

A recently published article, Ocelík et al. (2014), reports on the geometry of coatings created by overlap of individual tracks. We have proposed a recursive model for profile of such a coating using simplified physical assumptions. Defining the overlapping ratio,  $OR$ , i.e. relating track width with distance  $D$  between the centres of neighbouring tracks:

$$OR = (w - D) / w \quad (1)$$

The assumptions in the model are:

1. The width of the track is controlled by the dimensions of the laser beam (in case of laser cladding by the width of laser beam) and stays constant during the track overlap;
2. The character of the track profile shape is controlled by physical factors such as viscosity, surface energy of the melt, gravitational force, etc. and is not changed by overlap;
3. The amount of the clad material is constant during successive cladding tracks.

In mathematical sense the recursive model has been formulated as follows:

The width of the single track  $w$  is defined by the distance between points  $A_1$  and  $B_1$  on a horizontal axis, Figure 2. The profile of the first track is given by a known function  $F_1$ . A hypothetical position of the second, 'shifted' laser track with the same profile as  $F_1$  is marked by a dashed profile between points  $A_2$  and  $B_2$ . The overlap ratio  $OR$  is defined as the distance between points  $A_2$  and  $B_1$  divided by the track width  $w$ . The profile of the second overlapped track  $F_2$  has to be found on the base of function  $F_1$  and physical assumptions made above. Similarly, all other profiles are calculated recursively on the base of the previous one.

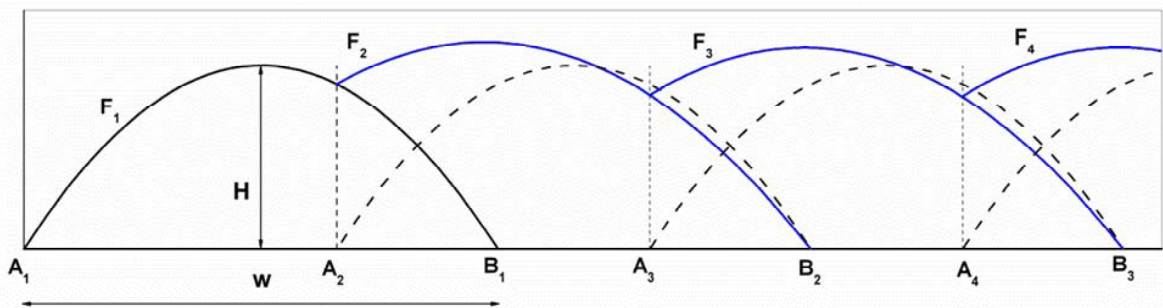


Fig. 2. Schematic representation of the recursive model, from Ocelik et al. (2014).

It is assumed that function  $F_1$  has an integral over an interval  $(A_1, B_1)$  and that this function is equal to zero outside of this interval. Let  $z = (1-OR)$ . The left point and the right point of  $n$ -th track are:  $A_i = wz(i-1)$ ,  $B_i = w + wz(i-1)$ ,  $i = 1, 2, \dots, n$ . Profile of  $F_i$  starts always on the previous profile  $F_{i-1}$  at point  $A_i$ :

$$F_i(A_i) = F_{i-1}(A_i) \quad \text{for } i = 2, 3, \dots, n \quad (2)$$

the profile of  $F_i$  goes to zero at point  $B_i$ :

$$F_i(B_i) = 0 \quad \text{for } i = 1, 2, \dots, n, \quad (3)$$

and finally, the amount of the material added in  $i$ -th track is the same as in the first track. Therefore:

$$\int_{A_i}^{B_i} F_i dx = \int_{A_1}^{B_1} F_1 dx + \int_{A_i}^{B_{i-1}} F_{i-1} dx \quad \text{for } i = 1, 2, \dots, n \quad (4)$$

The right side of eq. (4) represents the amount of new material added, plus material from previous track inside the overlap zone. Equations (2)-(3) are sufficient for model calculations when the functions  $F_i$  are functions of the same type determined by 3 parameters.

A number of different functions can be substituted into this model. We have examined parabolic, sinusoidal, elliptical and arc functions but any function that satisfied the aforementioned requirements of the model can be used, hence making this model very versatile. Figure 3 shows predictions of recursive model for different types of single

track shapes and wide range of overlaps, Ocelík et al. (2014). It has been shown several times, Cao et al. (2011) and Ocelík et al. (2014), that parabolic and circular shapes have prominent rank for a wide range of selected functions.

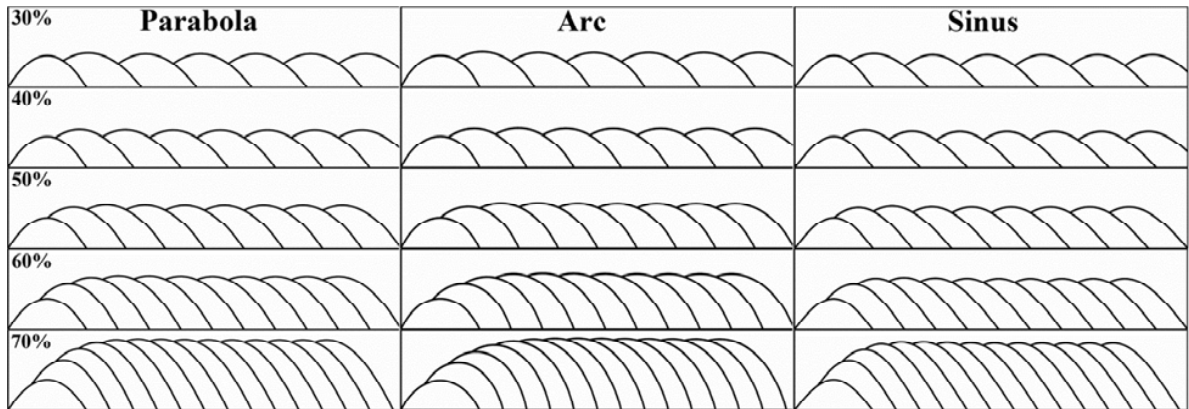


Fig. 3. Overlapped coating profiles calculated by recursive model for three different shapes of single track and five different ORs, from Ocelík et al. (2014).

Furthermore, the recursive model always converges to a stable shape, i.e. a constant height and waviness is achieved after a few tracks, as would be physically expected. Since coatings created using overlap of individual tracks result in a wavy surface the top layer has to be post-treated by machining before application in practice. For this reason it is useful to consider an *effective coating thickness*. This is the final thickness after machining and it depends on the coating height and coating waviness. The lowest point on a wavy surface, the ‘valley’ between overlapped tracks, corresponds to the *effective coating thickness*. For this reason the authors have tested the model comparatively for *relative waviness* and for *relative coating height*. Relative surface waviness of the coating is defined in accordance with previous studies, Paul et al. (2013), as:  $(\max(F_i(x)) - \min(F_i(x))) / \max(F_i(x))$  ( $i \gg 1$ ). Relative coating height is the height of the coating measured from the substrate compared to the height of an individual track.

The model was tested for a number of functions and compared to experimental data. The experiments were done for a range of  $H/w$  ratios of the single track clads. Interestingly the model predictions of the relative coating height and relative coating waviness were independent of  $H/w$  ratio and depended only on an overlap ratio,  $OR$ . There was a very good agreement with experiments and the parabolic function of the model which also gave an excellent prediction for an overall shape, i.e. the height and the waviness, of the profile of the laser clad coatings, figure 4.

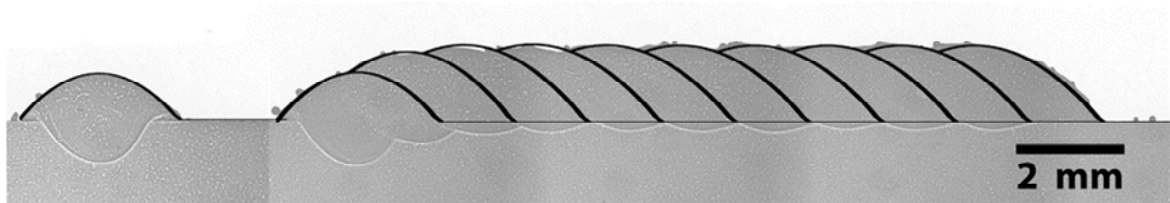


Fig. 4. Comparison of experimentally observed profile of a single track and coating prepared by coaxial cladding and calculated profile (black overlay) using parabolic shape function, from Ocelík et al. (2014).

Figure 5 shows experimental data for a range of different  $OR$ s for different laser cladding nozzles compared to model prediction using the parabolic function. With the exception of the side cladding for a nozzle with a small opening the data fits the model prediction very well. The purpose of this work is to build on these previous developments and combine them to produce a complete prediction of the laser clad geometry based purely on initial processing parameters that can be adjusted in each experiment.

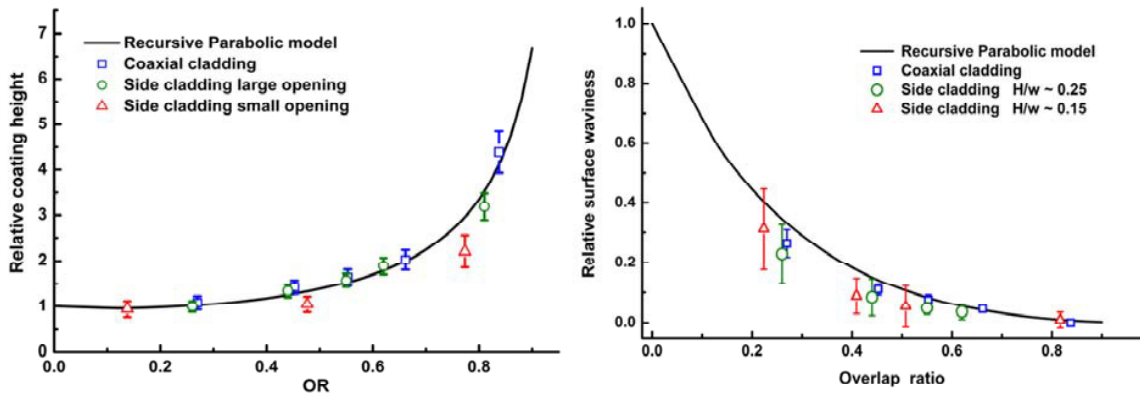


Fig. 5. Parabolic function for the recursive model plotted against experimental data for relative coating height (left) and relative surface waviness (right) as a function of  $OR$ , from Ocelik et al. (2014).

## 2. Prediction of coating geometry from $F$ and $S$

The dependencies for relative coating height and waviness as a function of  $OR$  predicted by the recursive model has been fit numerically using exponential functions. As Figure 6 clearly demonstrates these fits are excellent in overlap ratio interval 0.0-0.8. This gives expressions for relative coating height,  $H_{rel}$ , and relative coating waviness,  $W_{rel}$ :

$$H_{rel} = Ae^{\frac{OR}{\beta}} + C \quad OR < 0.8 \quad (5)$$

$$W_{rel} = Ae^{\frac{OR}{\beta}} + C \quad OR < 0.8 \quad (6)$$

$A$ ,  $\beta$  and  $C$  are constants that were determined numerically and listed in Table 1. The values have been determined from fits shown in Figure 6.

Table 1. Values of constants in equations (5) and (6) for relative coating height and relative coating waviness for the example of the parabolic function.

	$A$	$\beta$	$C$
Height	0.0454	0.205	0.862
Waviness	1.051	-0.253	-0.0327

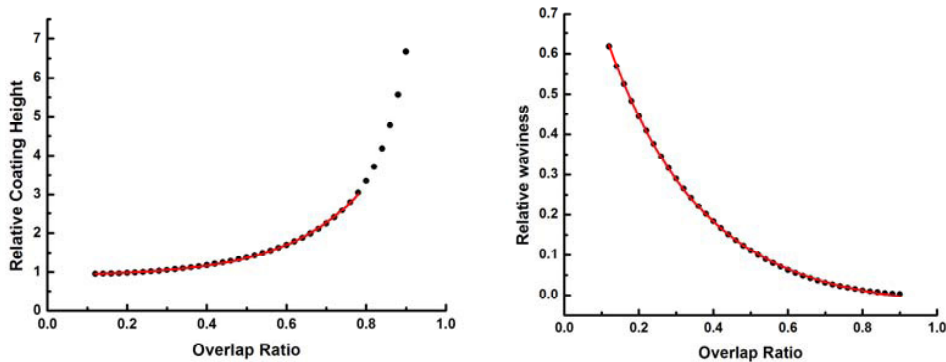


Fig. 6. Exponential fits for the overlap dependence for the relative coating height (left) and relative surface waviness (right).



It has to be noted that the relative coating height and the relative coating waviness only depend on the overlap ratio, i.e.  $H_{\text{rel}} = f(OR)$  and  $W_{\text{rel}} = f(OR)$ .

We have shown (de Oliveira et al. (2005) and Ocelík et al. (2007)), that the clad height,  $H$ , depends only on the scanning speed,  $S$ , and the powder feeding rate  $F$ , leading to the following dependence:

$$H = \alpha \frac{F}{S} + \gamma \quad (7)$$

where  $\alpha$  and  $\gamma$  have dimensions  $[m^2/kg]$  and  $[m]$ , respectively. Since the absolute value of the coating height, that is the height of the coating measured from the substrate, is a product of relative coating height and a single track height,  $H$ , we can combine equations (5), (6) and (7), to:

$$H_{\text{abs}}, W_{\text{abs}} = a \frac{F}{S} e^{\frac{OR}{\beta}} + b e^{\frac{OR}{\beta}} + c \frac{F}{S} + d \quad (8)$$

Which is a function containing only constants  $a$ ,  $b$ ,  $c$ ,  $d$  and  $\beta$ , processing parameters,  $F$ ,  $S$ , and an overlap ratio,  $OR$ .

The dimensions of the constants are  $[m^2/kg]$  for  $a$  and  $c$  and  $[m]$  for  $b$ ,  $d$  and  $\beta$  is dimensionless. Equation (8) is true for both: absolute height,  $H_{\text{abs}}$ , and absolute waviness,  $W_{\text{abs}}$ , though the constants will be different in each case. The constants are determined from the aforementioned constants in equations (5), (6) and (7) once the equations are combined.

### 3. Discussion

While equations (7) and (8) appear to show a convenient and simple description of the single track and coating geometry, the complete description is more complicated because the overlap ratio  $OR$  is not a processing parameter.  $OR$  depends on track width  $w$  and on *displacement*,  $D$ , between successive tracks. *Displacement* refers to distance between points  $A_1$  and  $A_2$  in Figure 2.

It was experimentally shown that width of the laser track,  $w$ , depends linearly on laser power,  $P$ , and scanning speed,  $S$  (de Oliveira et al. (2005) and Ocelík et al. (2007)):

$$w = \delta \left( \frac{P}{\sqrt{S}} \right) + \omega \quad (9)$$

where  $\delta$  and  $\omega$  have dimensions  $[m^{1/2} W^{1/2} s^{-1/2}]$  and  $[m]$ , respectively. Therefore, both relative coating height and relative coating waviness can be predicted directly from experimental processing parameters, thereby allowing a complete prediction of the geometry based only on processing parameters. The fact that constants  $\gamma$  and  $\omega$  in Eq. (7) and (9), respectively, are not zero reflects the situation that these dependencies were found experimentally with some statistical validity (see Figure 1). Equation (8) has been derived on the base of these statistical relations and therefore it also has this statistical meaning.

Equations (7) and (9) can be combined with the recursive model to predict coating profiles based on overlap of individual tracks purely from  $P$ ,  $S$ ,  $F$  and *displacement*,  $D$ , between successive tracks. Figure 7 shows results of the model predictions for a range of displacements and scanning speeds. The laser power and powder feeding rate are kept constant between individual plots for a more direct comparison, with  $P = 600$  W and  $F = 100$  mg/s.

These processing parameters have resulted in the following predictions of track width,  $w$  and single track height,  $H$ :

$S$	5 mm/s	10 mm/s	20 mm/s
$w$	<b>1.48 mm</b>	<b>1.33 mm</b>	<b>1.22 mm</b>
$H$	<b>0.62 mm</b>	<b>0.40 mm</b>	<b>0.28 mm</b>

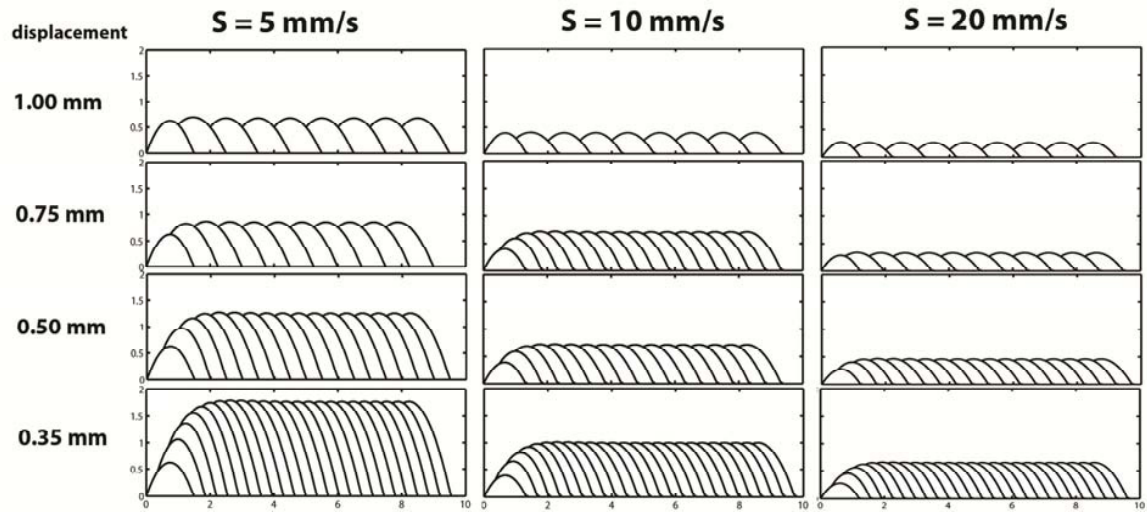


Fig. 7. Profiles of coatings formed by overlap of individual tracks calculated for laser cladding with three different scanning speeds and four different laser track displacements. The units on the axes of all the plots are in mm.

It can be clearly seen from the Figure 7 that the height of the coating decreases with increased scanning speed while the overlap and coating height increase with smaller displacement between tracks, which confirms the physical expectations. The decrease in final coating height with increased  $S$  is due to the fact, that feeding rate  $F$  is constant, and therefore amount of clad materials per unit length is decreasing with increasing  $S$ . Most importantly, Figure 7 plots show an entire geometry of laser clad coatings. Therefore, we demonstrate the possibility to predict the final geometry purely based on experimental inputs. A complete experimental work that will validate the prediction of single track geometry as well as coating shapes from laser cladding processing parameters is still required. The recursive model and relations between single track geometry and processing parameters are key for such a study.

#### 4. Conclusions

A simple but efficient method for the prediction of coating geometry for coatings formed by overlap of individual laser tracks in laser cladding has been presented. A full coating geometry can be predicted purely based on experimental inputs, namely scanning speed, laser power, powder feeding rate and displacement between successive tracks. Our equations contain experimental constants that depend on the particular set-up, but these can be determined experimentally leading to a convenient prediction of the final laser clad geometry.

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